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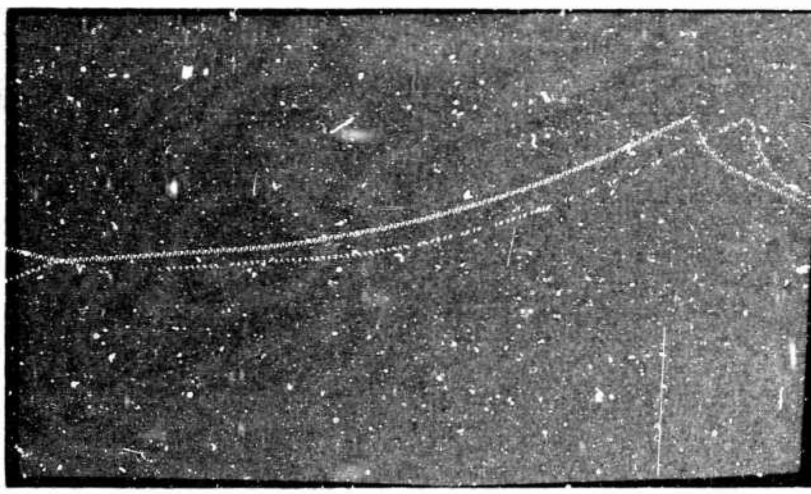

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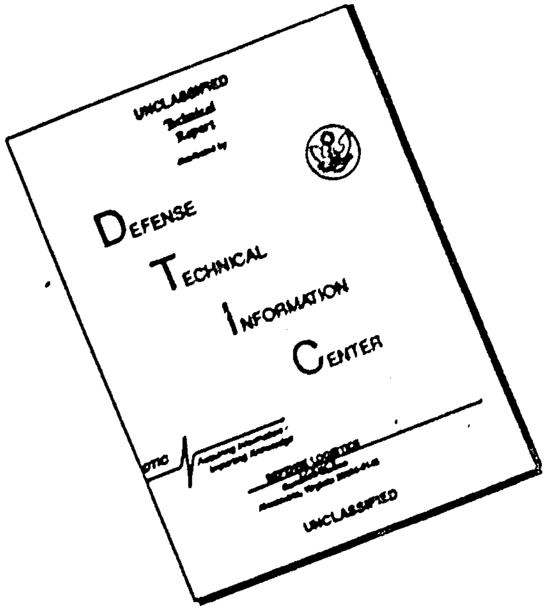

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University of South Carolina
Department of Electrical Engineering

Non-Waveguide Methods of Millimeter Wave, Transmission

R. G. Fellers and J. E. Sees

June, 1968

Research Sponsored by the Air Force Office of Scientific Research, Office of Aero Space Research United States Air Force Under Grant AF-AFOSR-3-65 Project-Task 9767-02

INTRODUCTION

Work on this subject "Non-Waveguide Methods of Millimeter Wave Transmission" has been in progress since April 1, 1956 under contract AF-18(603)-43 and under subsequent grants AF-AFOSR-61-53, AF-AFOSR-62-315, AF-AFOSR-3-63, and the just completed grant AF-AFOSR-3-65. The list of reports, papers, and publications occuring in this report includes those relevant to all of this work

BACKGROUND INFORMATION

The use of millimeter waves at frequencies from 30 gigahertz to 150 gigahertz, and even higher, has become feasible with the development of sources of power in these regions. These frequencies serve as valuable research tools and expand the usefulness of radio applications in the consumer, military, and space endeavors. At these frequencies it becomes practicable to build physically small high-gain antennas. Relatively small antennas may give the directivity needed for high-resolution radar systems, and security in communications and telemetry.

While these higher frequencies offer many advantages in addition to the compactness of systems, the problems of energy losses in wave-guides and other components become a serious deterrent when the conventional type components are used. For example, at 35 to 40 gigahertz the loss in a rectangular waveguide operating in the TE_{01} mode may run nearly three db per meter. Circular cylindrical wave guide operated in a TE_{01} mode reduces the losses very significantly but at the higher frequencies in this range free space propagation techniques appear to offer some distinct advantages over even the most efficient waveguide techniques.

RESULTS OBTAINED

Experimental results have indicated that transmission loss below that of rectangular dominant mode waveguide can be obtained between horns or parabolic antennas located relatively close together. This work has been carried out at a wavelength of 8.6 millimeters

for three different antenna sizes and preliminary work at 4.3 millimeters has been accomplished for two antenna sizes. These results are described in the report AFOSR TN-57-188, April 1957 and in AFOSR 11-72.

Evaluation of transmission loss around corners using shaped reflectors with single curvature has been undertaken and lower loss than that of straight line transmission has been observed. This is described in the report AFOSR TN-60-427, April 1960. Further investigation utilizing reflectors with double curvature has resulted in gains up to 6.90 dbs over straight line transmission for distances of about 25 meters. This has been reported in a master's thesis entitled "Reflector for Right Angle Transmission of Microwave Beams" by C.E. Bowen (1963) and in the final report on grant AF-AFOSR-62-315.

The dielectric sheet duplexer has been constructed and evaluated at 8.6 millimeters. This is described in the report AFOSR TN-60-14, January, 1960. The application of this sheet to an interferometer is also described. Extension of the use of this device to 4.3 millimeters has also been undertaken. Results are described in the report on grant AF-AFOSR-61-53.

The circular polarization duplexer has been successfully operated at 8.6 millimeters and is described in a paper "A Circular Polarization Duplexer for Millimeter Waves" published in the AIEE proceedings "Communications and Electronics," January, 1960.

A pair of closely spaced dielectric prisms has been successfully used in a duplexer, a directional coupler, and in an adjustable

attenuator. This work is described in the report AFOSR-TN-59-687, July 1959, for prisms with matching plates to eliminate reflections at the external surfaces. At shorter wavelengths the construction of such matching plates becomes difficult, and an analysis was undertaken to analyze theoretically the effect of internal reflections on performance. This work considering only first order reflections was described in a Master's thesis "An Evaluation of the Internal Reflections Inside Dielectric Prisms at Millimeter Wavelengths" by A. Chauvallon (1962). An extension of this analysis to include multiple reflections has been completed and published under the title "Internal Reflections in Dielectric Prisms" IEEE Trans. MTT-12, November, 1964, by R.G. Fellers and John Taylor.

By making use of prisms shaped so that the angle of incidence of the electromagnetic wave on the prism is Brewster's angle (the angle of zero reflection), it is possible to eliminate the reflections at the external air-dielectric interfaces of the prism and at least in principle to eliminate the multiple reflections which result in degraded performance and lowered directivity. Preliminary results were reported in a Master's thesis dated June, 1965, entitled "The Design of Dielectric Prisms with Minimum Internal Reflections at Millimeter Wavelengths" by Huang Kwang Ta.

Considerable work has been done on the computation of near zone (as close as $D^2/4\lambda$) antenna fields. An analysis has been carried out on the effect of shifting the feed of the antenna from the nominal focus position. It is possible to realize almost infinity gain at short distances by appropriate shift of the feed point. This work

is described in a Master's thesis "An Investigation of Defocus Phase Errors in Paraboloidal Reflectors" by William Marshall Leach (1964).

The theoretical analysis of the prism bi-directional coupler using Brewster's angle to eliminate reflections at exterior airdielectric interfaces has been extended and refined. New prisms have been constructed and more accurate experimental work has been carried out. The operation of this device is reviewed making use of figure 1. The incident wave strikes the exterior air-dielectric interface at Brewster's angle and all of the energy is transmitted into the dielectric. This same condition occurs at all exterior air-dielectric interfaces. The angle of incidence on the dielectric air interface at the gap is greater than the critical angle. In the absence of prism 2 all of the energy in this wave is reflected. If prism 2 is in contact with prism 1, the air gap is eliminated and all energy is transmitted through both prisms. By adjusting the gap width any desired division of energy between transmetted and reflected waves can be effected. Thus the device functions as an adjustable bi-directional coupler.

The energy transmitted and reflected can be computed theoretically as was described in the report AFOSR-TN-57-687. Expressions for the ratios of transmitted power and reflected power to incident power are reproduced below in convenient form making use of figure 2.

$$(1) \quad \frac{\text{Transmitted Power}}{\text{Incident Power}} = \frac{S_3}{S_1} = \frac{4n^2\cos^2\theta}{D}$$

$$(2) \quad \frac{\text{Reflected Power}}{\text{Incident Power}} = \frac{S_r}{S_1} = \frac{1}{D}\left[\frac{(Mn)^2+\cos^2\theta}{M}\right]^2 \sinh^2(\beta_o Md)$$

where $M^2 = n^2\sin^2\theta-1$

$$D = \left[\frac{(Mn)^2-\cos^2\theta}{M}\right]^2 \sinh^2(\beta_o Md)+4n^2\cos^2\theta\cosh^2(\beta_o Md)$$

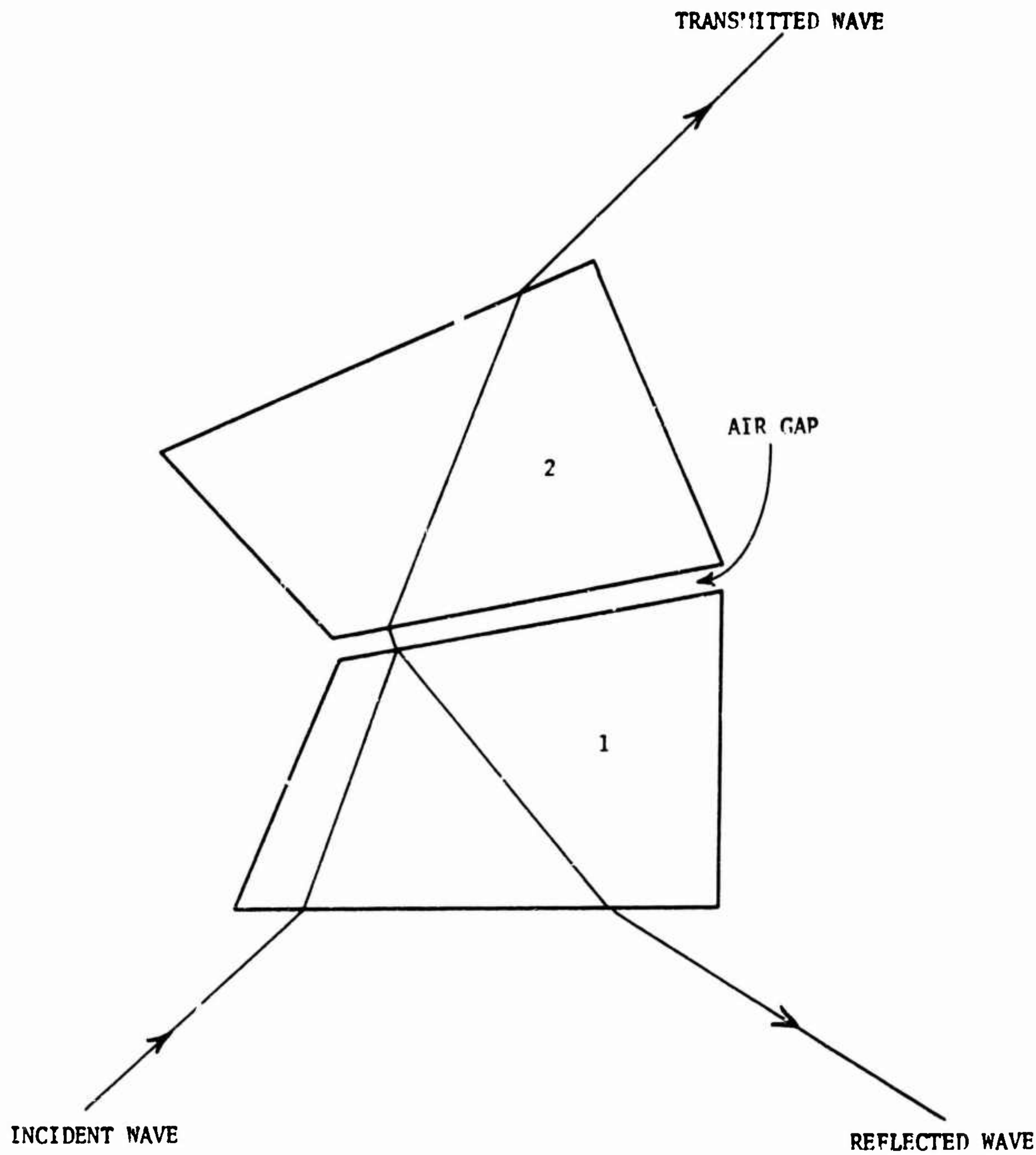
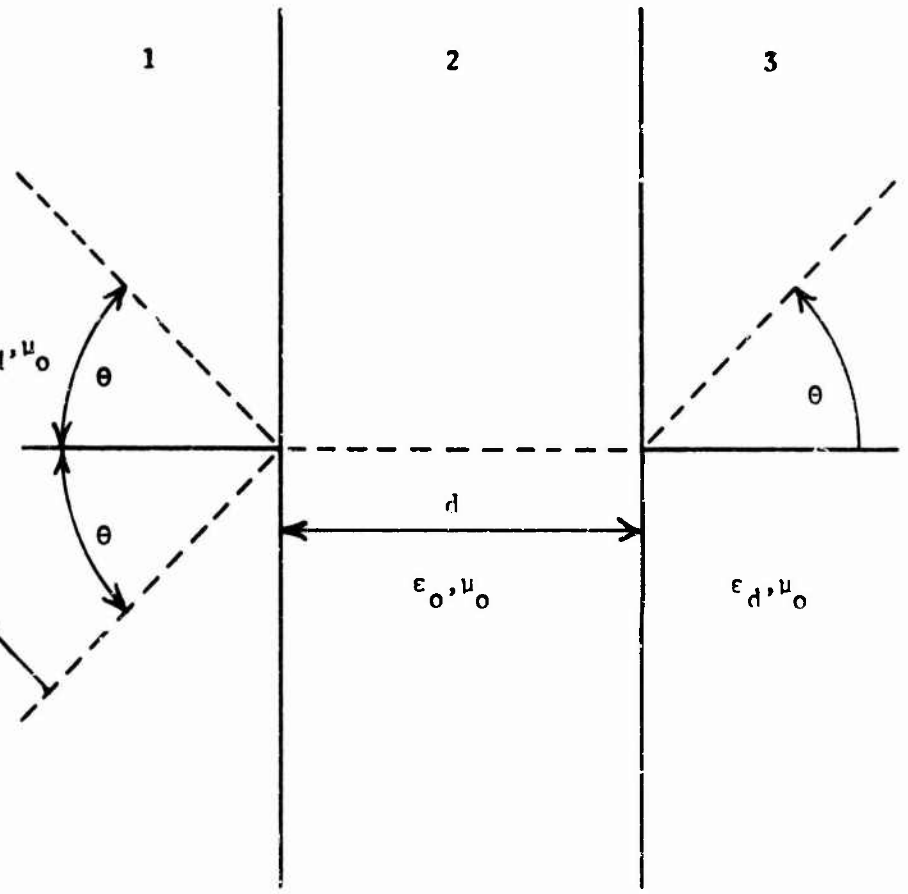


FIGURE 1

TOP VIEW OF PRISMS

FIGURE 2

AIR GAP USED IN THE ANALYSIS



LIST OF SYMBOLS

ε_d = dielectric permittivity

ε_o = permittivity of free space

d = air gap

S_3 = transmitted poynting Vector across air gap

S_1 = incident poynting vector

θ = angle of incidence

μ_o = permeability of free space

$n = \sqrt{\varepsilon_d/\mu_o}$ = index of refraction

$M^2 = n^2\sin^2\theta - 1$

$\beta_o = \omega\sqrt{\varepsilon_o\mu_o}$

S_r = reflected poynting vector

$$D = \left[\frac{(Mn)^2 - \cos^2\theta}{M}\right]^2 \sinh^2(\beta_o Md) + 4n^2\cos^2\theta\cosh^2(\beta_o Md)$$

ω = frequency in radians per second

In the analysis of the bi-directional coupler, the microwave beam is assumed to be a plane wave of finite cross-section and equations (1) and (2) are assumed to hold. Obviously, this is a simplification of a complex problem. As a result of the assumptions, power is not conserved. That is, $\frac{S_3+S_r}{S_1} \neq 1$. However, the theorectical curves exhibit the experimental behavior of the device.

Experimental measurements were carried out a frequency of 33.52 gigahertz using prisms with relative dielectric constant equal to 2.34 Results are plotted in figures 3 and 4. The most recent phase of this work undertaken has been a preliminary study to evaluate reflections in terms of surface defects and structural deformations.

A detailed knowledge of the effects of surface errors upon the gains and patterns of paraboloidal antennae is extremely important in the design and the manufacture of antennae having very high gains

FIGURE 3

TRANSMISSION LOSS VERSUS AIR GAP

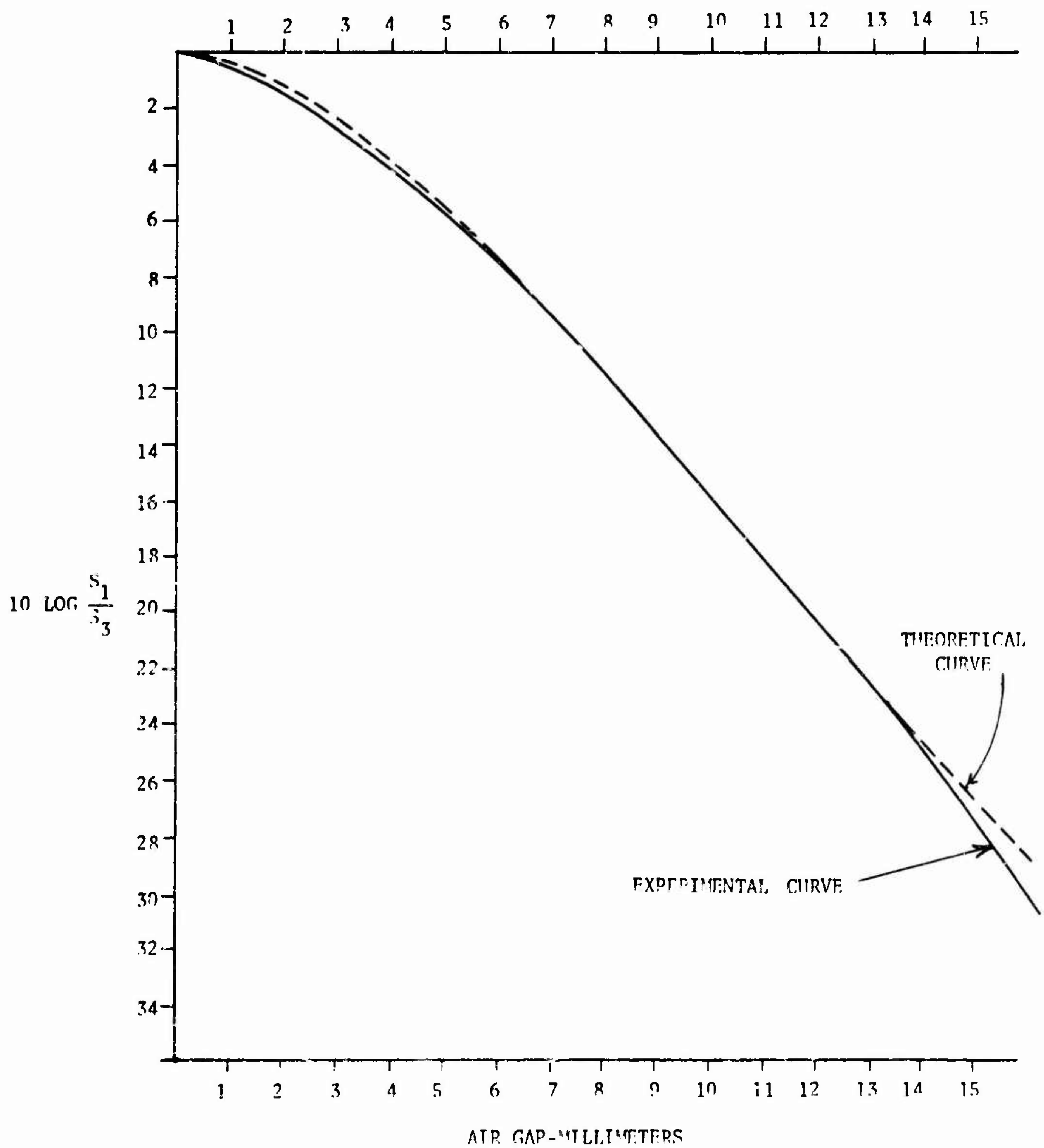
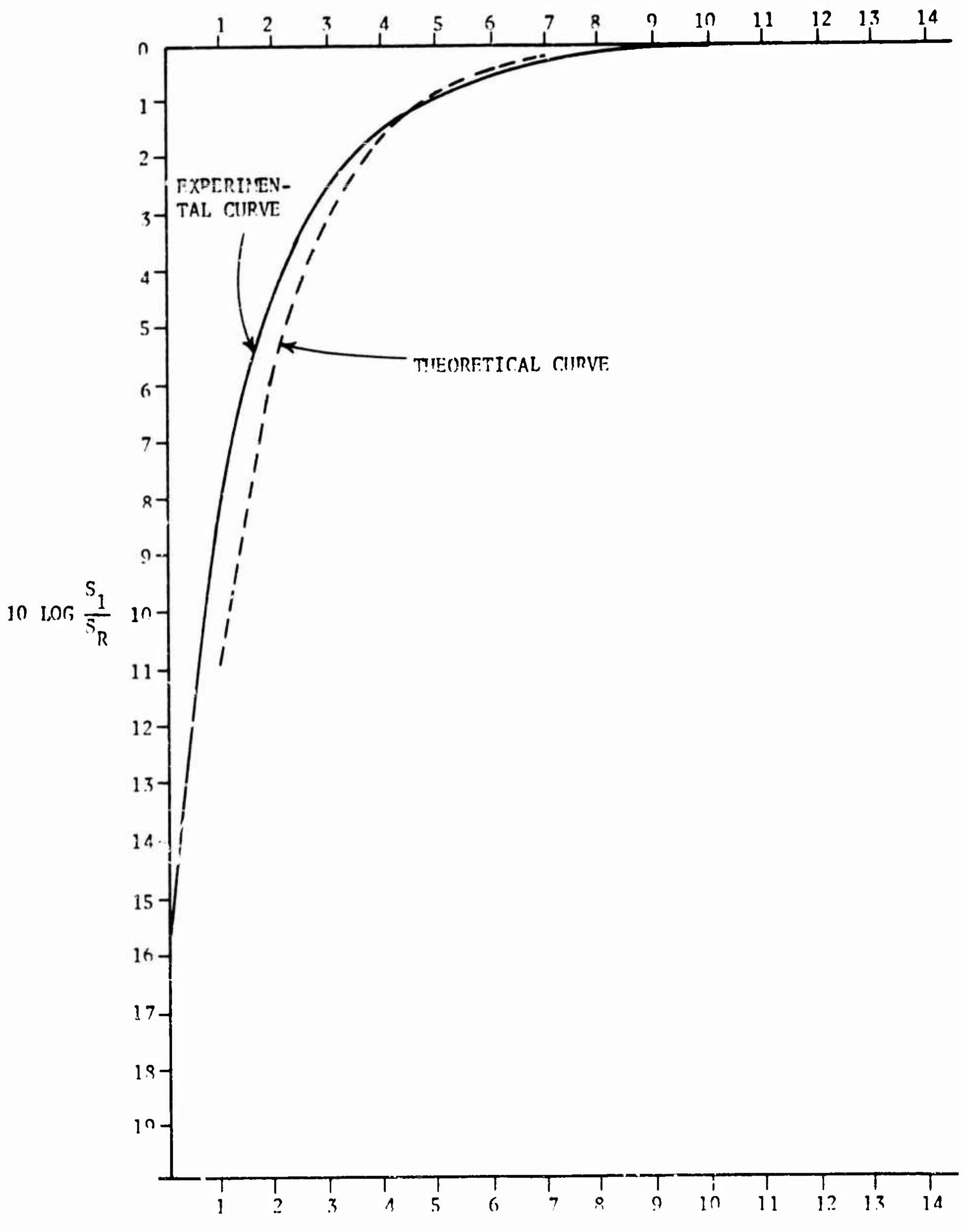


FIGURE 4

REFLECTION LOSS VERSUS AIR GAP



and narrow beams. In general, when the diameter of a reflector is made quite large relative to the operating wavelength random and systematic surface deviations occur which cause significant deteriorations in gains and radiation patterns. These surface errors normally arise from several interrelated causes, and frequently it is neither mechanically nor economically feasible to reduce all of them to negligible magnitudes. Herein lies a real need for more meaningful criteria than are presently available for effectively evaluating the relative importance of various kinds of surface errors in predicting antenna performance and for specifying designs.

Systematic surface deviations may occur from environmental conditions. Deflections result from accelerations or gravitational forces, from wind pressures or viscous drags, from thermal gradients and differential expansion, and from metal fatigue or relaxation processes. Other systematic errors are often unintentionally built into a structure and result from design features and manufacturing techniques. Sometimes, for example, it may be necessary after fabricating and machining have been completed to disassemble a reflector and transport it to another geographical or space site where it must be reassembled for use.

A better knowledge of the relative importance of specific types of surface errors and of their distributions or locations on the reflector surfaces is needed for establishing more realistic design and construction specifications than are possible at the present time. Conceivably this knowledge could open up additional

possibilities of deliberately controlling spoilage of selected surface regions to achieve special antenna characteristics. To cite a specific example, one might reduce the spill-over and the consequent back pick-up by bringing the higher-order side lobes of the antenna feed into the paraboloidal reflector and then deliberately spoiling the surface regions which reflect the destructively interfering side lobes. Another example would be the use of controlled spoilage to permit using a single reflector simultaneously or alternately at two different frequencies.

ANALYSES

For a beginning phase of the current investigation a two zone paraboloidal antenna has been chosen in which the deviation from a true paraboloid is a simple step in the surface. The main lobe and first side lobe of the antenna feed are included within the reflector with the step in the surface located approximately at the null in the feed pattern between the main lobe and the first side lobe. In these preliminary analyses it has been assumed also that the second null in the feed pattern falls at the outer edge of the parabola. This model avoids compounding the complexities of analysis with too many types of surface deviations and yet represents a useful application. If the step in the surface is made one-quarter wavelength in magnitude the first side lobe from the feed is reflected in phase with the principal lobe and augments the signal in the main lobe of the reflected pattern.

A solution of this type analysis has been programmed for the

IBM 7040 computer. The program is sufficiently flexible to permit using analytical functions to represent the feed pattern and to describe the reflector surface. To date no provision is made to account for law of reflection at the reflector surface. For example, the coefficient of reflection at an element of area of surface depends upon the angle of polarization and upon the angles of incidence and scatter and these factors are not included.

A second program has been written to read in the surface from a matrix in which the position of each element of the surface is represented by an element of the matrix. This program permits entering point-by-point measurements of a surface without considering a parabola or any specified reference surface. In the present state of the program it does not include the effects of polarization or angle of incidence at the individual elements. These factors may be included in the above programs after the programs have been more thoroughly tested and debugged.

PATTERN RANGE

A pattern range and other instrumentation have been further developed to perform the experimental work related to this project. An antenna pedestal has been moved from the roof of the three-story Engineering Building to the roof of the nine-story Physical Science Building. The control and recording equipment are housed in a room immediately below the antenna pedestal. No means has been incorporated for operating the system from the roof level near the base of the pedestal but this may be done if it appears necessary.

At present the instrumentation at the other end of the range is

housed in the corner of a room which was once the press gallery and is the highest location at the University Stadium. The range distance between the Physical Science Building and the University Stadium is approximately 1.72 miles. Along the line of sight are commercial buildings but these lie several degrees below the path of propagation and it is not anticipated these will appreciably affect the measurements. Other locations are available for the transmitter end of the range when needed. These will afford ranges from a few thousand feet up to possibly ten miles.

The pedestal is a Scientific Atlanta Model 5420-7 aximuth positioner with a model 5230-7 elevation positioner and it has a train accuracy of $\pm$ 6 seconds of arc within a sector of about 10 degrees of the propagation path. The recording equipment consists of Scientific Atlanta Series 1520 rectangular recorder for making x-y plots of antenna gain against pointing angle measured in the train plane.

TRANSMITTER

An 8-millimeter source is used at the Stadium end of the range. A single unit including an 8 millimeter oscillator with calibrated attenuator, a wavemeter, and a horn are mounted outside the window of the press box when the range is to be operated. At other times this equipment is stowed inside the power supply and auxiliary components. Vernier adjustments provide means of accurately aiming the transmitted signal at the receiving antenna.

TEST ANTENNA

The antenna pedestal will readily accommodate paraboloidal reflectors up to twenty feet in diameter and will handle vertical loads of approximately 30,000 pounds. With some divising, obstructions could be removed and larger diameter antennae could be used if this were necessary.

Taking advantage of scaling our antenna size and frequency we have started with a main paraboloidal reflector five feet in diameter and have a three-foot diameter paraboloid which will be cut for use as a center portion and to be off set from the main surface as described earlier. A frequency of approximately 35 gigacycles is being used. The center portion of this antenna will reflect the main lobe from the feed pattern and the exposed portion of the five-foot paraboloid one-quarter wave behind the center section will reflect the first side lobe of the feed pattern.

Although the shapes of the test reflectors deviate from true paraboloids these have been selected for close tolerances to simplify the analysis, the intentions being to retain a high degree of axial symmetry, and to concentrate more on the zonal study first.

SUMMARY

The feasibility of transmission between two closely spaced antennae has been established with transmission loss lower than that of rectangular waveguide. Defocus of antenna feeds has improved performance. Transmission around corners at no loss has been demonstrated. The use of a dielectric sheet as a power divider has been proved effective. A circular polarization duplexer has been developed. A pair of dielectric prisms has been used very effectively as an adjustable bi-directional coupler, as an attenuator and as a duplexer. The effect of reflections at prism surfaces has been analyzed and an effective means of controlling them has been devised.

The effect of surface distortions on antenna performance has been analyzed and a computer program has been written to compute for zone field under these conditions. Application has only been made to an idealized symmetrical case. A high precision antenna pattern range has been set up to evaluate experimentally the patterns from distorted antennae. Only preliminary measurements have been made.

Reports and Publications

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Non-Waveguide Transmission of Millimeter Waves, R.G. Fellers and W.E. Probst, April 15, 1957, ASTIA Document Number AD126483, AFOSR TN-67-188.

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Reflector for Right Angle Transmission of Microwave Beams, C.E. Bowen, 1963.

An Investigation of Defocus Phase Errors in Paraboloidal Reflectors, W.M. Leach, 1964.

The Design of Dielectric Prisms with Minimum Internal Reflections at Millimeter Wavelengths, Huang Kwang Ta, 1965.

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"A Circular Polarization Detector for Millimeter Waves." R.G. Fellers. Communication and Electronics AIEE, January, 1960, pp. 934-937. (District IV Prize Paper).

"Non-Waveguide Methods of Millimeter Wave Transmission." R.G. Fellers. Microwave Journal, Vol. 5, pp. 80-86, May, 1962.

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"Measurements in the Millimeter to Micron Range." R.G. Fellers. Proceeding of the IEEE, Vol. 55, No. 6, June, 1967.

Professional Personnel Who Participated in the Research

Faculty Members

R.G. Fellers - Ph.D., Yale - 1943

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Professional Personnel Who Received Degrees As A Result Of Research Performed with AFOSR Support On This And Prior Grants

F.E. Rouffy, Jr. - MSEE - Univ. of South Carolina - 1960

A.L. Chauvellon - MSEE - Univ. of South Carolina - 1962

C.E. Bowen - MSEE - Univ. of South Carolina - 1963

W.M. Leach - MSEE - Univ. of South Carolina - 1964

Huang Kwang Ta - MSEE - Univ. of South Carolina - 1965

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3. REPORT TITLE

NON WAVEGUIDE METHODS OF MILLIMETER WAVE TRANSMISSION

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Final

5. AUTHOR(S) (Last name, first name, initial)

Fellers, Rufus G.
Sees, James E.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 June 1968	19	20

8a. CONTRACT OR GRANT NO. AF-AFOSR-3-65 b. PROJECT NO. 9767-02 c. 6144501F d. 681301	9a. ORIGINATOR'S REPORT NUMBER(S) None 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFOSR - 68-1346

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